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Effects of the Index Finger Position and Force Production on the Flexor Digitorum Superficialis Moment Arms at the Metacarpophalangeal Joints- an Magnetic Resonance Imaging Study

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Abstract

Background—The purpose of this study was to use magnetic resonance imaging to measure the moment arm of the flexor digitorum superficialis tendon about the metacarpophalangeal joint of the index, middle, ring, and little fingers when the position and force production level of the index finger was altered. A secondary goal was to create regression models using anthropometric data to predict moment arms of the flexor digitorum superficialis about the metacarpophalangeal joint of each finger.

Methods—The hands of subjects were scanned using a 3.0T magnetic resonance imaging scanner. The metacarpophalangeal joint of the index finger was placed in: flexion, neutral, and extension. For each joint configuration subjects produced no active force (passive condition) and exerted a flexion force to resist a load at the fingertip (active condition).

Results—The following was found: (1) The moment arm of the flexor digitorum superficialis at the metacarpophalangeal joint of the index finger (a) increased with the joint flexion and stayed unchanged with finger extension; and (b) decreased with the increase of force at the neutral and extended finger postures and did not change at the flexed posture. (2) The moment arms of the flexor digitorum superficialis tendon of the middle, ring, and little fingers (a) did not change when the index metacarpophalangeal joint position changed ($p > 0.20$); and (b) The moment arms of the middle and little fingers increased when the index finger actively produced force at the flexed metacarpophalangeal joint posture. (4) The moment arms showed a high correlation with anthropometric measurements.

Interpretation—Moment arms of the flexor digitorum superficialis change due to both changes in joint angle and muscle activation; they scale with various anthropometric measures.

Keywords

MRI; moment arm; flexor digitorum superficialis; finger interaction

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1. Introduction

Precise coordination of the fingers is necessary in order to perform numerous everyday tasks. The contact forces produced by fingertips result from the interaction of numerous architectural and physiological properties of the hand, forearm, and central nervous system (CNS). A better understanding of these properties is crucial for advancing many fields concerned with hand function such as motor control, biomechanics, motor disorders, rehabilitation and finger related surgeries (i.e. tendon transfers, joint replacements, etc.). It is well known that altering the angles of finger joints significantly affects the maximal fingertip force and the moments about the joints (Kamper et al. 2006). The effects of one finger activation and/or position changes on other fingers are much less understood.

Individual finger movements are not independent of other fingers (reviewed by Schieber and Santello 1994) due to: 1) mechanical links provided by connective tissue (Fahrer 1981; Kilbreath and Gandevia 1994; Leijnse 1997), 2) multi-finger motor units in the extrinsic finger muscles (Kilbreath and Gandevia 1994; Schieber 1995), and 3) overlapping cortical representations of the finger muscles (Schieber and Hibbard 1993; Sanes et al. 1995; Rathelot and Strick 2006). The result of these constraints is a behavior referred to as enslaving (Zatsiorsky et al. 1998, 2000): When a single finger *intentionally* moves or produces force, other fingers also *unintentionally* move or produce force. It is generally accepted that enslaving is due to a combination of the three previously mentioned constraints on individuated finger movements; however, the relative contribution of each is unknown. It is unknown whether the activation of the finger flexors of one finger and/or change of the finger position will change the moment arms of the flexors of other fingers.

Magnetic resonance imaging (MRI; Wilson et al. 1999; Fowler et al. 2001), as well as cadaver based methods (Brand et al. 1975; Armstrong & Chaffin 1978; Youm et al. 1978; An et al. 1983) has previously been used to measure moment arms (MAs) of the flexor digitorum superficialis (FDS) and flexor digitorum profundus (FDP) muscles about the metacarpophalangeal (MCP) finger joint. The Wilson et al. (1999) study used 3D MRI imaging to compute the moment arm of the FDP with the index finger positioned in various flexion postures. Moment arms were computed using: (a) a 3D tendon excursion method, (b) a 3D geometric method, and (c) a 2D geometric method. All three methods were found to produce approximately the same mean moment arm values per posture; however, the variance between repeated measurements was lowest for the 3D tendon excursion method and highest for the 2D geometric method. In the Fowler et al. (2001) study 3D MRI imaging was applied on a single female subject to compute 3D moment arms of multiple muscles that cross the distal interphalangeal (DIP), proximal interphalangeal (PIP), and MCP joints. Again, only passive force production was investigated. Both studies found an increase in the moment arm at greater flexion angles.

In the cadaver studies tension was applied to the extrinsic flexor tendons to artificially simulate active force production (Brand et al. 1975; Armstrong & Chaffin 1978; Youm et al. 1978; An et al. 1983). This may not be an accurate depiction of what occurs *in vivo* as *in vivo* muscular force development may be different. Co-contraction of other muscles crossing the MCP joint is neglected and the cadaver hand data may not be an accurate representation of a young, healthy hand. These studies all found that as the flexion angle of the MCP joint increased the moment arms of the FDS and FDP also increased. Another significant finding was that the center of rotation of the MCP was located at the geometric center of the MCP head (Youm et al. 1978).

To the best of our knowledge, the effects of the muscle force levels on the moment arms of the fingers have not addressed in the literature. With regard to other joints, the data are

scarce and controversial. Zatsiorsky et al. (1985) and Aruin et al (1987) applied a pulling force to the *m. triceps surae* of a cadaver leg and did not find substantial changes in the magnitude of the moment arms while Maganaris et al. (1998, 1999) and Maganaris (2004) found large changes in moment arms of the tibialis anterior and Achilles tendon during maximum voluntary contractions (MVC) at the ankle compared to rest. At the wrist level, a change in tension of one of the extrinsic flexor tendons has been shown to change the moment arm of that tendon and transmit force to neighboring tendons (Agee et al. 1998).

Unfortunately, many of the previous studies are limited in that they have: (1) been performed on cadavers, and/or (2) only looked at passive conditions in which no active contraction of the muscle was occurring. The purpose of this study was to measure *in vivo* changes in moment arms of the flexor digitorum superficialis (FDS) about the metacarpophalangeal (MCP) joints of the 2-5 fingers due to: (1) changes in joint posture of the index finger MCP joint and 2) changes in muscle force production levels (passive vs. active flexion force). A secondary goal was to create regression models using anthropometric data to predict moment arms of the FDS about the MCP joint of each finger.

2. Methods

2.1. Subjects

Ten male subjects volunteered to be in the study. The subjects were all young, healthy and had no history of musculoskeletal injury or disease of the upper limbs. Subjects provided informed consent and the experiment followed a protocol that was approved by the Institutional Review Board of the Pennsylvania State University.

2.2. Experimental Procedure

Prior to the MRI scan a number of anthropometric measures were taken from the subjects (Supplementary Material Table S1). Supplementary Fig. S1 provides an illustration of the boundary points of specific measurements. Hand length was measured from the most distal crease at the wrist to the tip of the longest finger. Hand breadth was measured on the palmar surface at the level of the MCP joints of fingers 2-5 with the fingers in a relaxed state of ab/adduction. Measurements of the fingers were taken on the dorsal surface. Phalange distances were measured from the approximate joint centers, based on visual inspection. Phalange circumferences were measured around the approximate midpoint of each phalange. Individual and four-finger flexion MVCs were recorded. Subjects placed their four fingers on unidimensional force transducers (208C02, PCB Piezotronics, Depew, NY, USA) and were instructed to press as hard as they could for five seconds. Two trials of each MVC were recorded and the average computed.

2.3. MRI Equipment and Scans

The MRI scans were performed using a 3.0 Tesla MRI scanner (Siemens Magnetom Trio 3T, Siemens Corporation, Germany) at the Social, Life, and Engineering Imaging Center (SLEIC) facility of the Pennsylvania State University by a trained MRI technician. Subjects were required to lay prone on the scanning table with their right arm extended, above their head, inside of the head coil and positioned in the custom made finger positioning apparatus (Fig. 1). The index finger was in three MCP joint postures: 1) Neutral (0 degrees), 2) Flexed (30 degrees of flexion), and 3) Extended (15 degrees of extension). The middle, ring, and little fingers were lightly taped together so that their posture did not change during the scans. The distal interphalangeal, proximal interphalangeal, and MCP joint postures of the non-index fingers was 180° for all scans. For each index finger MCP posture two sets of scans were obtained: 1) passive force and 2) active flexion force. The passive scans were always performed first. The subjects were then removed from the scanner and a 400 g mass was

hung from the apparatus then looped around their index fingertip. The suspended load generated an extension moment about the MCP joint. To resist the load, subjects had to produce a small active flexion force with their index finger. It was necessary to use a low amount of resistive force since subjects were required to maintain the contraction for several minutes. For most subjects the suspended load required them to exert 10-15% of their index MVC during the active flexion force scans. After the scan was completed subjects were removed from the scanner, the index finger was repositioned and the passive and active scans were obtained for the next posture. The index finger MCP joint was positioned in neutral posture first, followed by flexion and then extension. Two minutes of rest were given after completion of the active flexion force scans. The entire time to collect all of the scans was less than an hour.

For each combination of force level and index finger posture, localization and a T1 weighted 2D sagittal scans were taken. The time required for the localization and 2D sagittal was 0:51 and 1:53 min, respectively. The voxel size of these images was $0.7 \times 0.7 \times 3.0$ mm (width $\times$ height $\times$ depth). The localization scan was aligned along the long axis of the index finger. The other fingers were positioned as parallel as possible to the index finger. Using this slice thickness (3.0 mm), 35 slices were sufficient to scan entirely through the 2-5 fingers of all subjects. The TR (repetition time) and TE (echo time) values were 1380 ms and 11 ms, respectively. The flip angle was 120° . Multiple pilot tests were performed to optimize the scan quality while minimizing the scan time. Reduction of scan time was important as longer times caused subjects to become fatigued during the active pressing scans, as well as, experience discomfort from lying with the arm extended overhead. Fatigue and discomfort both led to movements by the subjects that decreased the scan image quality.

2.4. Data Processing and Analysis

Processing and analysis of the images was performed using Syngo Viewer (Siemens Corporation, Germany) and Matlab (Mathworks, Massachusetts, USA). For each index finger position and force production level single images of the sagittal scan slice passing closest to the center of the metacarpal head, of each finger, in the medial-lateral direction were identified. These images were saved and exported for further analysis. For each subject a total of 24 images comprised the data set (3 index finger postures $\times$ 2 activation levels $\times$ 4 fingers = 24). Only the FDS tendon was analyzed because its boundaries were most clearly identifiable in all of the images. Moment arms were computed using a 2D geometric method in which the moment arm was taken as the perpendicular distance from the line of action of the FDS tendon to the center of rotation at the MCP joint. Based on previous research we assumed that the center of rotation of the MCP joint was located at the center of curvature of the distal surface of the carpal head that articulates with the proximal phalange (Youm et al. 1978; Unsworth et al. 1979).

The images were imported into custom Matlab program for digitizing. Five points along the tendon line of action and ten points along the outer contour of the carpal head were digitized. The center of curvature was computed and assumed to be the center of rotation. The perpendicular line from the center of rotation to the tendon of action was then calculated. The length of the perpendicular line was then computed, which was the moment arm. This procedure was repeated five times for every image. The average of the five computations was calculated and was used as the moment arm for the given finger and condition. In nearly all cases the standard deviation of the five measurements was less than 0.2 mm. The actual index MCP angle was measured from the sagittal image slices to ensure subjects maintained the correct hand posture during the scans. Small deviations ($\pm 5^\circ$) from the set angles on the positioning apparatus did occur.

2.5. Statistics

Moment arms were averaged across subjects and the standard deviation computed. A separate repeated measure ANOVAs were performed to examine the effect of index finger MCP posture (3 levels: flexion, neutral, extension), and force (2 levels: non-zero, zero) on moment arm values of each finger. To examine the effect of force level on change in moment arm (tested response = Δ moment arm = moment arm under passive force condition minus moment arm under active flexion force condition) a separate repeated measure ANOVA was performed for each finger. The factor was index finger MCP posture (3 levels: flexion, neutral, extension). Repeated measure ANOVAs were performed using the statistical software SPSS (SPSS Inc., Chicago, IL, USA). Statistical significance was set to $\alpha = 0.05$.

Stepwise regression models were constructed to predict moment arm values based on anthropometric measurements taken from subjects. The models included the first and second order terms, along with the measured index MCP joint angle. The first order terms were the measurement values and the second order terms were the measurement values squared. The data for all index finger MCP postures during the passive force condition were used to create separate models for each finger. Only the circumference and length measurements of the finger whose moment arm was being modeled were included in the stepwise regression model. The significance level to include a predictor in the model was set to 0.25. Stepwise regression was performed using Minitab software (Minitab Inc., State College, PA, USA).

3. Results

The results for the moment arm values of the index finger will be presented first, followed by the moment arm results of the other fingers. Lastly the regression models of moment arms based on various anthropometric measurements will be presented.

3.1. Index Finger Moment Arms

The moment arm values for the index finger were largest in the MCP flexed posture and decreased as the finger moved to the MCP neutral posture (Fig. 2). The average values of the moment arms were similar for the neutral and extended index finger MCP posture.

For the flexion index finger MCP posture under the active flexion force condition the moment arm were slightly larger (13.3 (1.3) mm) than for the passive force condition (12.5 (1.0) mm). However, the opposite tendency was seen for both the neutral and extended index finger MCP where the average moment arms were slightly smaller under the active flexion force condition (neutral: 10.8 (1.0) mm; extended: 10.5 (0.7) mm) compared to the passive force condition (neutral: 11.2 (0.7) mm; extended: 10.9 (0.6) mm). The FDS moment arm of index finger was significantly affected by the index finger MCP posture ($F_{2,18} = 68.708$, $p < 0.001$), but not by force ($F_{1,9} = 0.936$, $p > 0.9$). The interaction effects of index finger MCP posture $\times$ force were also highly significant ($F_{2,18} = 6.679$, $p < 0.01$). Using pair-wise comparisons, the differences in moment arm for the neutral ($p < 0.05$) and extended ($p < 0.05$) index finger MCP posture were estimated as significant; however, they were not statistically different in the flexed index finger MCP posture ($p > 0.05$). Additionally, the range of moment arm values across subjects was statistically greater ($p < 0.05$) for the active flexion force condition (mean range = 2.9 (1.2) mm) than for the passive force condition (mean range = 2.5 (1.1) mm).

The percent changes in moment arms for flexion and extension, as compared to the neutral index finger MCP posture, are shown in Fig. 3. Flexion under active flexion force and passive force conditions both increased the moment arm. The active flexion force condition showed a larger increase than the passive force condition (approx. 24% vs. 12% increase).

Extension of the index finger decreased the moment arm by approximately the same amount for both passive force and active flexion force conditions (approximately 3% decrease).

3.2. Middle, Ring and Little Finger Moment Arms

The average moment arms for the middle, ring, and little fingers under different conditions are shown in Fig. 4. In general, middle finger moment arms were the largest (range across conditions: 10.8 (1.0) mm to 11.5 (0.6) mm) followed by the ring finger (range across conditions: 10.1 (0.7) mm to 10.5 (0.7) mm), and the little finger (range across conditions: 9.1 (0.6) mm to 9.7 (0.4) mm) had the smallest moment arms (Fig. 4). The repeated measure ANOVA results indicated that the effect of index finger MCP posture ($p > 0.2$ for all non-index fingers) and force of index finger ($p > 0.1$ for all non-index fingers) were not significant on the moment arms of the middle, ring, and little fingers. The effect of the interaction of index finger MCP posture $\times$ force was significant for all fingers except the ring finger ($F_{2,18} = 0.559$, $p > 0.5$).

3.3. Regression Modeling

The stepwise regression models demonstrated that moment arm values are fairly well correlated with anthropometric measurements. Squared values of the correlation coefficients ranged from 0.89 (index finger) to 0.68 (little finger) for the individual finger models (Table 1). The circumference of the proximal and middle phalanges was present in several of the models. The measured index MCP joint posture was present in the middle and little finger models. The parameters that reduced the largest amount of error in the model were the proximal phalangeal circumference, hand breadth (first and second order terms), total finger length, and hand length.

The index finger moment arms predicted using the regression model were compared to the experimental values of all subjects, for the neutral, passive force condition only (Table 2). The largest difference between the experimental and predicted value was -0.8 mm; however, for all other 9 subjects the absolute magnitude of the differences was 0.3 mm or less.

An example of the regression equation calculation for the MA of the index finger is presented below:

$$\begin{aligned} \text{Index MA} = & 90.130 + (-0.039 \times \text{Measured Index MCP Angle}) \\ & + (-29.980 \times \text{Proximal Phalange Circumference}) \\ & + (2.771 \times \text{Middle Phalange Circumference}) \\ & + (-3.158 \times \text{Distal Phalange Length}) + (0.113 \times \text{Subject Height}) \\ & + (0.055 \times \text{Proximal Phalange Length}^2) \\ & + (2.371 \times \text{Proximal Phalange Circumference}^2) + (-0.097 \times \text{Subject Weight}) \end{aligned}$$

For Subject 1 the equation is:

$$\begin{aligned}
 \text{Index MA} = & 90.130 + (-0.039 \times 179.7^\circ) \\
 & + (-29.980 \times 6.1\text{cm}) \\
 & + (2.771 \times 5.8\text{cm}) \\
 & + (-3.158 \times 2.5\text{cm}) + (0.113 \times 170.0\text{cm}) \\
 & + (0.055 \times (5.0\text{cm})^2) \\
 & + (2.371 \times (6.1\text{cm})^2) \\
 & + (-0.097 \times 73.0\text{kg}) = 10.15\text{mm}
 \end{aligned}$$

Experimentally measured Index MA = 10.22 mm. Hence the difference is less than 1 mm.

In summary, the following findings were reported: 1) The moment arm of the FDS at the MCP joint of the index finger increases with the joint flexion ($p < 0.005$, see Fig. 2) and stays unchanged with the finger extension. 2) The moment arm of the FDS at the MCP joint of the index finger decreases with the increase of the muscle activation level at the neutral ($p < 0.05$) and extended ($p < 0.05$) finger postures and does not change significantly at the finger flexed posture. (3) The moment arms of the FDS tendons to the middle, ring, and little fingers did not change significantly when the MCP joint posture of the index finger changed (Fig. 4). (4) The effects of the interaction of the MCP joint posture $\times$ force by the index finger were statistically significant for all fingers except the ring finger; (5) The FDS moment arms showed a relatively high correlation with basic anthropometric measurements which allowed developing regression equations that can be used for estimating the MA values.

4. Discussion

All subjects showed an increase in moment arm of the FDS about the MCP joint of the index finger as the finger was moved from neutral position to flexion, which was true for both passive force and active flexion force conditions. These findings, as well as the recorded magnitudes of moment arms, are in agreement with previous research (Brand et al. 1975; Armstrong & Chaffin 1978; Youm et al. 1978; An et al. 1983; Wilson et al. 1999; Fowler et al. 2001). Figure 5 summarizes the moment arm results.

The complex relations between the moment arms and the index finger MCP posture and force factors are most likely due to the complex muscle architecture. At the level of the MCP joint both the FDS and FDP tendons pass through the flexor sheath. The FDS has a larger moment arm about the MCP joint than the FDP; thus the FDS is typically recruited more for high force production tasks than the FDP (Brand & Hollister 1999). There are also pulleys along the finger that hold the tendon's close to the bone to prevent bowstringing, which consequently limit the amount by which the moment arm of these tendons can increase. The advantage of smaller moment arms of the flexor tendons is that small muscle-tendon excursions result in large joint motion. The lack of observed change of moment arm from the neutral to extended index finger MCP posture may have been due to wrapping of the tendons about the head of the metacarpal bone, which limited further reduction of the moment arm from neutral to extension. The points of insertion of the FDS and FDP should also be considered. The FDP tendon inserts on the distal phalange while the FDS tendon inserts on the middle phalange of each finger. The contribution of the FDS to the force that was produced could have been enhanced if the loop was placed around the middle phalange instead of the distal.

The fact that some changes in moment arms of the non-index, the middle and little, fingers were observed supports the notion that connections among the fingers limit their independence. The changes that occurred in moment arms are not necessarily due only to mechanical connections between the fingers. A study by Kilbreath and Gandevia (1994) showed, using intramuscular EMG, that when a single finger was instructed to flex to lift a weight as low as 2.5% MVC for that finger the EMG activity in other (non-instructed) fingers showed an increase. In turn, the increase of force by the enslaved fingers can induce their moment arm changes, e.g., due to bowstringing effects. It is worth to note that the ring finger MA was the only one not affected by the interaction of force and index finger MCP posture (Table 1B). In the literature on the finger enslaving, the effects of mechanical connections between the fingers were discussed solely in terms of the inter-tendinous transfer of pulling forces (Fahrer 1981; Kilbreath and Gandevia 1994; Leijnse 1997). This study adds a new dimension to this discussion: not only the forces but also the tendon moment arms can be changed as a result of force production by one of the fingers.

The stepwise regression models showed that anthropometric measurements can be used to quickly approximate MAs without the need to use MRI or other imaging methods to scan subjects. The circumferences of the phalanges of the finger's MA that is being measured appear to be the most important measurement to predict the MA, based on the stepwise regression models. Generally, these terms reduced the most error (sequential sum of squares) and had the most significant p-values. Models such as these can be valuable in the area of modeling muscle mechanics to predict how altering certain parameters would affect function. In particular, such models could be used by surgeons to design implants or determine the best possible manner in order to repair a tendon on a subject-by-subject basis (Wu et al. 2010).

There were several limitations or assumptions used that could be changed in future studies to improve the accuracy and overall quality of the data. Although the tendon excursion and 3D geometric methods have been shown to yield slightly more precise moment arm values (in terms of smaller standard deviations when the same moment arm is repeatedly measured using one of the above mentioned methods (Wilson et al. 1999) we chose to use the 2D geometric method. The 3D scans require longer scan times, which were difficult to achieve during active force production. Some subjects felt discomfort from the position they were required to lay in during the measurements and thus had difficulty maintaining the required level of force during the entire scan time. The reason why 3D scans could not be obtained by reconstructing the 2D scans is that the slice thickness was too large to reconstruct images with good enough resolution to accurately measure the moment arms in 3D. The slice thickness (3.0 mm) was as large as it was because the scans had to be performed through the entire hand, in the media-lateral direction, in order to be able to measure the moment arms for each finger. To compensate for our choice of using the 2D geometric method every moment arm was measured five times and an average value was computed. Applying the load at different points of the finger, namely at the middle phalange, could also have improved the study. However, since the level of force production was constrained to remain low this may have been ineffective in further recruiting the FDS. Applying the load to the fingertip allowed for the greatest external moment about the MCP joint to be produced.

5. Conclusions

The main findings were: (1) Moment arms of fingers change due to both changes in joint angle and muscle activation; (2) Changes in one finger's force production and posture can cause changes in other finger's moment arms; (3) Moment arms of the FDS scale with various anthropometric measures.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Fig. 1.
Schematic of finger positioning apparatus

Fig. 2.

Average index finger FDS moment arm values. Error bars are standard deviations. Single stars indicate a significant difference between passive and active conditions for a given index finger position using a pair-wise comparison test. Double stars indicate a significant difference between positions.

Fig. 3.
Percent changes in index finger FDS moment arm values compared to the neutral position for passive and active conditions. Error bars are standard deviations.

(A) Middle finger

(B) Ring finger

(C) Little finger

Fig. 4.

Average finger moment arm values for: (A) middle, (B) ring, and (C) little fingers. Error bars are standard deviations. Stars indicate a significant difference between passive and active conditions for a given index finger position using a pair-wise comparison test.

Fig. 5.

Schematic of index finger moment arms in the flexed, neutral, and extended positions. Mean and standard deviations of moment arms, under passive force and active flexion force conditions, are given for each position. The p-value for pair-wise comparisons between passive force and active flexion force conditions for each position are given.

Table 1

Stepwise regression models for individual finger moment arm values. First and second order anthropometric measurements were used in models. Measured index MCP angle assumes full extension of the MCP joint is 180°, flexion is a decrease from 180° and extension is an increase from 180°. The predictor coefficient is the coefficient multiplier of the factor in the multiple regression equation.

Index Finger MA			
Predictor	Predictor Coefficient	p-value	Sequential Sum of Squares
Constant	90.130	0.116	-
Measured Index MCP Angle (deg)	-0.039	0.000	15.58
Proximal Phalange Circumference (cm)	-29.980	0.092	6.46
Middle Phalange Circumference (cm)	2.771	0.001	1.70
Distal Phalange Length (cm)	-3.158	0.002	1.34
Subject Height (cm)	0.113	0.000	0.78
Proximal Phalange Length ² (cm ²)	0.055	0.077	0.62
Proximal Phalange Circumference ² (cm ²)	2.371	0.079	0.56
Subject Weight (kg)	-0.097	0.000	0.07
R ² = 0.888			
Middle Finger MA			
Predictor	Predictor Coefficient	p-value	Sequential Sum of Squares
Constant	370.500	0.011	-
Middle Phalange Circumference ² (cm ²)	-131.220	0.010	7.56
Middle Phalange Circumference (cm)	11.500	0.009	4.97
Distal Phalange Circumference ² (cm ²)	0.284	0.003	3.38
Hand Length ² (cm ²)	0.014	0.001	2.05
Measured Index MCP Angle (deg)	0.009	0.110	0.88
R ² = 0.711			
Ring Finger MA			
Predictor	Predictor Coefficient	p-value	Sequential Sum of Squares
Constant	-42.870	0.054	-
Proximal Phalange Circumference (cm)	2.910	0.000	6.15
Distal Phalange Length ² (cm ²)	-6.875	0.043	0.76
Hand Breadth ² (cm ²)	-0.003	0.769	0.57
Subject Weight (kg)	-0.056	0.012	0.56
Distal Phalange Length (cm)	33.110	0.053	0.49
R ² = 0.749			
Little Finger MA			
Predictor	Predictor Coefficient	p-value	Sequential Sum of Squares
Constant	-97.660	0.000	-
Hand Breadth ² (cm ²)	-1.439	0.000	1.69
Measured Index MCP Angle (deg)	0.015	0.001	1.39
Middle Phalange Length ² (cm ²)	-0.400	0.006	1.39

Index Finger MA			
Predictor	Predictor Coefficient	p-value	Sequential Sum of Squares
Middle Phalange Circumference ² (cm ²)	−0.026	0.657	1.25
Hand Breadth (cm)	24.704	0.000	0.97
Total Finger Length ² (cm ²)	−0.029	0.103	0.41
R ² = 0.684			

Table 2

Comparison of experimental moment arm values to predicted moment arm values for the index finger in neutral posture and passive condition. All models are for the passive condition.

Subject	Moment Arm		
	<i>Experimental</i>	<i>Predicted</i>	<i>Difference</i>
1	10.2	10.2	0.0
2	12.0	12.2	-0.2
3	10.4	10.7	-0.3
4	11.2	11.4	-0.2
5	11.9	12.0	-0.1
6	11.0	10.9	0.1
7	11.5	11.4	0.1
8	12.1	12.2	0.1
9	10.8	11.1	-0.3
10	11.2	12.0	-0.8